

An Integrated Coastal Observation and Flood Warning System: Rapid Prototype Development

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Abstract - This paper describes the rapid prototype development of an inaugural capability for an Integrated Coastal Observation and Flood Warning System (ICOFWS), initially focused in the tidal Potomac River. A collaboration of the Virginia Institute of Marine Science (VIMS), NOAA National Weather Service (NWS) Forecast Offices in Wakefield and Sterling, Virginia, and Mitretek Systems developed the capability for a high-resolution hydrodynamic storm-surge model, coupled with the newest generation Weather Research and Forecast model and high resolution digital elevation LIDAR data, to predict land inundation from storm events in the Washington Metropolitan Area and the tidal Potomac River. This prototype capability then uses emerging Geographic Information Systems (GIS) visualization technologies to present forecast information in a manner that can be integrated into operations systems of local jurisdiction emergency managers and other planners. Initial steps have been taken to document a proposed process to bring this capability into operational status within the standard NWS forecast cycle as a tool to support storm surge products. It is being explored for use by partners of the Chesapeake Bay Observing System (CBOS) within the Integrated Ocean Observing System (IOOS) Mid-Atlantic Coastal Ocean Observing Regional Association (MACOORA) to demonstrate the interaction of organizations operating in, and providing support within, the Chesapeake Bay region, as well as potential use of this collaborative procedure within other IOOS regional associations throughout the United States. This focused systems engineering approach allows for the more-rapid-than-typical development of prototype systems that can be evaluated for use within the broader IOOS and Global Earth Observation System of Systems (GEOSS) to provide more timely support to those with the responsibility to prepare for, and react to, environmental effects on critical infrastructure and our society.

I. INTRODUCTION

To paraphrase an old saying about politics, “all flooding is local.” This is especially true for the Metropolitan Washington, DC Area on the banks of the upper tidal Potomac River. The driving influences for flooding along the Potomac River are the upstream riverine discharge and the storm surge from the Chesapeake Bay. The potential energy stored in 18 trillion gallons of water in the nearly 200-mile-long Chesapeake Bay is constantly ready to deliver devastation along nearly 5,000 miles of coastline during a storm event [1]. For example, Hurricane Isabel was a relatively mild Category 2 hurricane when it made landfall on the NC coast in

September, 2003. It weakened to a tropical storm as it moved through southern Virginia, but it still produced an 8-foot storm surge and destroyed or damaged more than 4,000 homes and impacted the broad spectrum of infrastructure throughout the Chesapeake Bay region. A future stronger hurricane could magnify those totals to unprecedented levels [2].

Emergency managers rely on the National Oceanic and Atmospheric Administration’s (NOAA’s) National Weather Service (NWS) to predict the height and timing of the storm surge from hurricanes and major storms. The current NWS capability uses a general hydrodynamic model — Sea, Lake and Overland Surges from Hurricanes (SLOSH) — that is applied to coastal waters and estuaries to estimate the likely height of water at the shoreline for tropical storms. The NWS Meteorological Development Laboratory (MDL) model provides information for storm surge from non-tropical storms. The emergency managers then use this information, along with relying on their personal experience with previous events, to estimate what areas will flood. The current NWS capability works fairly well in many areas, but it has limitations and deficiencies in some areas, such as the tidal Potomac River in the Washington Metropolitan Area and along portions of the Chesapeake Bay, such as Baltimore and Annapolis which suffered far worse flooding than did Washington from Hurricane Isabel.

In recent years, the emerging generation of storm-surge prediction capabilities has greatly advanced and consists of better hydrodynamic models driven by improved wind-field models. A feature of these hydrodynamic storm surge models is the ability to model land inundation to predict flooding directly, rather than providing only the height of water at the shoreline. Given the catastrophic damage caused by hurricanes in 2005, local, state, and federal governments have recognized the critical need for a better planning strategy in responding to these natural hazards. In late 2005, the Mitretek Sponsored Research (MSR) Program began collaborating with the Virginia Institute of Marine Science (VIMS) of the College of William and Mary, and the NWS Forecast Offices (WFO) in Wakefield and Sterling, Virginia, to develop and demonstrate the capability of the high-resolution storm-surge model augmented by input from the newest generation Weather Research and

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Forecast (WRF) model operated by the NWS.

The purpose of the Mitretek-coordinated project was to develop a prototype capability of an Integrated Coastal Observation and Flood Warning System (ICOFWS). The prototype would (1) predict land inundation from storm events in the Washington Metropolitan Area and the tidal Potomac River, (2) provide the results of the predictions to emergency managers using emerging visualization technologies, (3) demonstrate the value of improved methods to emergency managers and planners, and (4) document what would need to be done to bring this capability into operational status at the NWS. An associated goal was to develop a capability that would directly benefit the Chesapeake Bay Observing System (CBOS) within the Mid-Atlantic Coastal Ocean Observing Regional Association (MACOORA) of the Integrated Ocean Observing System (IOOS).

A wind-field model was coupled to a hydrodynamic flooding model of the Chesapeake Bay and its tributaries to provide the prediction of land inundation. We identified the atmospheric and water-level data network in the region that provides input to the models and the visualization and other techniques to communicate the results of the flooding predictions. We then addressed how we have begun to work with regional emergency managers and planners to ensure that what is produced meets their initial needs and identifies what remains to be done to provide a fully operational capability.

II. ATMOSPHERIC AND HYDRODYNAMIC MODELS

A. Atmospheric Wind-Field Model

The Chesapeake Bay topography serves a significant role in many weather situations over the mid-Atlantic region. Currently, the finest resolution model from the NOAA National Centers for Environmental Prediction (NCEP) has a horizontal resolution of 12 km. This resolution is insufficient for properly simulating hydrodynamic conditions in the Chesapeake Bay and its tributaries. To improve forecasts of smaller-scale weather events near the Chesapeake Bay, a higher-resolution model is necessary for input to these forecasts. The model chosen for this is the Science and Training Resource Center WRF environmental modeling system (EMS), which is a complete modeling system that can be tailored to run for a local area on a WFO workstation. Figure 1 provides the domain for the model.

The NWS Wakefield WFO has incorporated this model to run at approximately a 4-km horizontal resolution, which provides significantly greater resolution and addresses details of the bay's influences on the weather. The analysis and initialization fields come from a Local Area Prediction System (LAPS) analysis that incorporates all observational data available in Wakefield's Advanced Weather Interactive and Processing System (AWIPS). This data includes observational networks, such as Physical Oceanographic Real-Time System (PORTS), road and weather information provided by the Virginia Department of Transportation, and numerous other local and

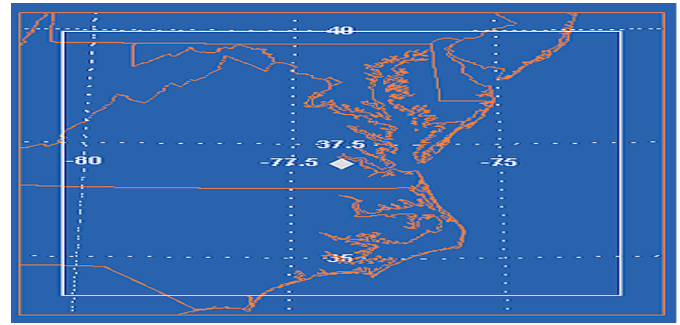


Figure 1. The WRF Model Domain

regional mesonet data sets that enable LAPS to produce an improved detailed analysis for the region and results in an improved model initialization. The new atmospheric wind-field model capability provides more detail in tropical systems (e.g., hurricanes) and winter storms (e.g., nor'easters) and improves detection of local wind-field effects in tributaries and along the coasts.

B. High-Resolution Storm-Surge Model

The storm surge and its impact on the coastal regions depend on the intensity of atmospheric forcing, the path of the storm, characteristics of bathymetry, and the shape and size of the water body. Additionally, the moon phase that can generate abnormally high water levels and freshwater flow into the river from inland regions will augment the magnitude of the surge. Numerical techniques are frequently used for storm-surge simulation [3], and it is essential to have adequate grid shape and a sufficiently high resolution to resolve inter-tidal zones and their properties to accurately simulate coastal surge and inundation.

In the Chesapeake Bay, the myriad waterways are inherently complicated and consist of many tributaries and coastal basins. For an accurate representation, a high-resolution grid on the order of 50–100 meters with mixed triangular and quadrilateral cells was generated for its irregular shorelines and inter-tidal zones. The total number of cells for the Chesapeake Bay unstructured grid is about 420,000, with 120,000 covering the water body, and another 300,000 covering the inter-tidal zone. This simulation of storm surge in a very large model domain requires considerable computer resources to maintain the extremely high grid resolution,

The ELCIRC (Eulerian Lagrangian Circulation) model, one of the recently developed, cutting-edge finite volume/finite difference models employing unstructured grids, overcomes these obstacles. It was successfully used for the simulation of storm tide with excellent performance during Hurricane Isabel of 2003 in the Chesapeake Bay as described in [4] and [5].

ELCIRC was developed by [6] based on [7]. The model uses an orthogonal, unstructured grid with mixed triangular and quadrilateral grid cells in the horizontal and the z grid in the vertical. Such a grid conforms to the complex geometry and shipping channels naturally without additional coordinate transformation. The grid size can also be adjusted to be finer

where it needs to be and coarser where it does not. The other advantage of the model is that it uses a semi-implicit, finite-difference scheme to update the momentum equation, which has a superior feature of calculating wetting-and-drying robustly in the inter-tidal zone. Lastly, but as importantly, the Eulerian-Lagrangian (E-L) transport scheme used in the calculation of the convective terms is not restricted by the Courant-Friedrichs-Levy (CFL) condition. Because of this property, the high-resolution model, with a grid resolution as small as 30 meters, can use a three-minute time step for the storm tide simulation in the Chesapeake Bay, which saves 100-fold computing time when compared to the traditional numerical method limited by the CFL condition, as described in [8] and [9]. Figures 2 and 3 provide an example of the geography and resulting grid, respectively, for the model that was used for the initial reconstructions in this project. The model runs produced for initial evaluation were based

on Hurricane Isabel. Figure 4 provides forecast and observed water level heights at various stations throughout the Chesapeake Bay, and overall there is extremely good verification. The model results used in the left side of Figure 5 provide a similar depiction for sensors in the upper tidal Potomac River, but they do not show the same degree of correlation based on the storm surge prediction from the hydrodynamic model. There has been considerable interest in determining if including the outflow from the upper Potomac River would provide improved verification. The model run that produced the right side of Figure 5 includes the increased river flow resulting from on-land rainfall that drains into the upriver tributaries and typically arrives in Washington a day or more after the original storm’s passage. It is evident that the model now includes that contribution, and there is much closer correlation between the model prediction and the observed water level.

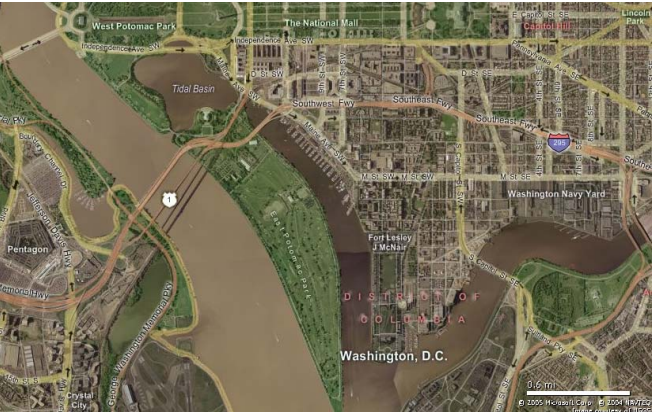


Figure 2. Example of geography for model grid.

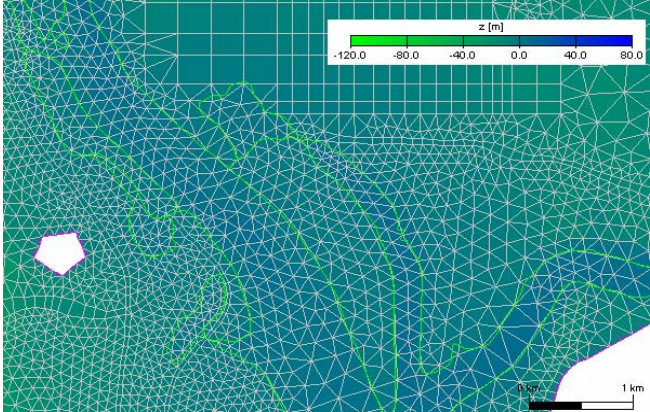


Figure 3. Example of hydrodynamic/inundation model grid.

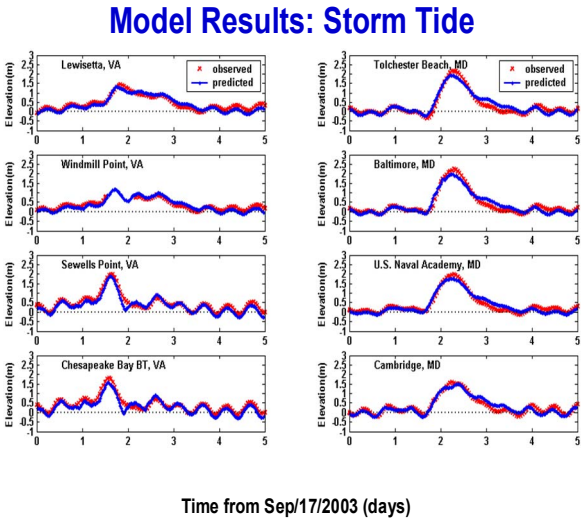


Figure 4. Hurricane Isabel model reconstruction results.

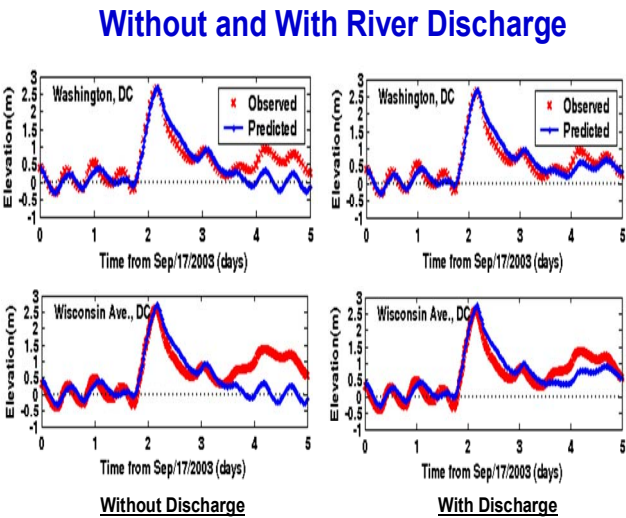


Figure 5. Example of hydrodynamic/inundation model grid.

C. Atmospheric and Water Data Network Integration

An integrated coastal-observation and flood-warning-system forecasting model requires readily available observational data from atmospheric and water sensors in the Chesapeake Bay and Potomac River region. As part of this work, we surveyed the available observation sensors through the Chesapeake Bay Observing System (<http://www.cbos.org/>) of MACOORA and IOOS. We then began an analysis of the observation data pattern to determine if any observational gaps existed and if any upgrades to the current observational network were required. Initial recommendations for the next steps to implement an observation network that can support an operational working model in a forecasting mode were then developed.

Our search for observational sensors began with a review of websites of federal and state agencies, universities, and other organizations. Although there was some overlap, there was no single location to collect the information. In addition, the team looked for “ghost” sensors, i.e. sensors that are collecting data, but the data are not being shared beyond the original user. To evaluate gaps in the sensor data, we worked with the modelers to determine what inputs were needed, the accuracy and precision of these inputs, the timeliness of the data, and the locations from which data would be most important. We then evaluated available inputs, identified gaps, and pursued options to improve the current observation situation. For example, the collaboration of the U.S. Geological Survey, CBOS, and Mitretek resulted in the installation of a new sensor mid-way on the Potomac River near the U.S. Highway 301 Bridge. This now provides an observation location essentially half-way between the sensors in Lewisetta, VA (near the mouth of the river) and the upriver sensors in the Washington, DC and Alexandria, VA area. Most importantly, it is an alternative for the sensor in Colonial Beach, VA that was destroyed by Hurricane Isabel and has not been replaced.

Since the purpose of this initial work was to demonstrate an enhanced prototype capability and not to deploy an operational system, the final objective involved planning for a system-engineering-focused analysis to determine the required changes to the observational network that would enable these systems to support an operationally deployed forecasting model. This analysis would look at both the location of sensors within the network and the current communication systems, survivability, and power systems. The findings of this analysis would offer recommendations for modifying existing, or adding new, sensor platforms, as well as listing further analysis or steps that will be required for this network to support an operational forecasting model. Installation and sponsorship of additional sensors in CBOS to provide a more comprehensive observation network within the Potomac River as an element of IOOS for MACOORA are being pursued.

D. Visualizing the Predicted Water Level

Communicating flood predictions to emergency managers, first responders, and the public before and during a storm event is an extremely important part of the forecasting system. The

NWS currently uses textual products to provide the forecast of the height of water expected at the shoreline. This project investigated visualization methods to provide more useful output. The NOAA Storm Surge Leadership Team recently reported findings based on their assessment of user needs [10]. Two of the four major findings served as guiding principles for this element of the project. One finding was that users of these analyses and forecasts need inundation information and historical maps in displays and outputs that are as “user friendly” as possible without compromising the data. The other finding was that users need community-level risk and vulnerability information for emergency planning, coastal management, and land-use planning.

This project addressed public service functions that employ Geographic Information Systems (GIS) tools within existing operations. Examples include police departments, fire and rescue departments, and emergency dispatchers in moderate to large municipalities. Since first responders will continue to rely on existing GIS support infrastructure to support operations, the ICOFWS needs to deliver inundation analysis and forecast products in a format compatible with users’ organic GIS display capabilities. This approach will also allow evaluation of forecasted effects on critical infrastructure with lead time to take preparatory actions, where feasible, and prepare for restoration and recovery efforts where necessary.

The other visualization effort addressed needs of the general public and first responders in smaller communities where GIS capabilities may not exist. In these cases, graphical inundation analyses and forecasts that are accessible using a web browser promise to reach the broadest cross-section of the user community. The proliferation of mapping and display tools, such as Google Earth®, is facilitating enhanced capabilities to deliver products to the public rapidly and interactively. The ICOFWS has taken the first steps to construct prototype flooding inundation model output data into geographically referenced overlays and images and integrate them into Internet display tools for evaluation by potential end-users to determine what products will best meet their requirements.

Taking an approach such as this of providing products to users that are either end-state or used as input into GIS systems is a significant potential enhancement to currently provided services, but the geospatial scale of this prototype demonstration presents new challenges to the visualization component that have to be considered. The accuracy and resolution of the Digital Elevation Models (DEMs) and Light Detection And Ranging (LIDAR) tiles describing the area of interest are critical to the accuracy of the associated graphical representations of the inundation. A gradual ground elevation slope means that small errors in land elevation have the same impact as errors in water-level analyses and forecasts and can result in large errors in the depicted horizontal extent of inundation. There is also a need for an understanding of water flow and frictional components that can be assessed as water flows over different terrain (e.g., grass, open soil, concrete, or asphalt) or between buildings and other structures.

Orthometric and water-level data must be compliant with recognized standards, and data transformations are required to compare geospatial data obtained from diverse sources. In addition, mapping and display capabilities must take into account limitations in the resolution and accuracy of supporting geospatial data so that display products do not convey a sense of accuracy that is beyond the resolution of the supporting data. The North American Vertical Datum of 1988 (NAVD 88) has been affirmed as the official civilian vertical datum for the United States by the Federal Geodetic Control Subcommittee [11]; similarly, NOAA has adopted the National Tidal Datum Epoch (NTDE) of 1983-2001 as the official tidal datum reference period for all tidal data monitored as part of the National Water-Level Network. A continuing element within this work involves leveraging both of these datum standards where practical, as well as the NOAA VDatum tool, to provide for the needed interactive transformations between tidal, orthometric, and ellipsoidal datum elevations.

As shown in sample output examples in Figures 6 and 7, the GIS work in this project used ArcGlobe®, which has a look-and-feel similar to Google Earth®. In this system, images and features (points, lines, and polygons) are draped over a base elevation dataset. One can use either the global elevation dataset or add his own. In this case, we initially used the USGS National Elevation Dataset (NED) with 30-meter resolution for the upper Potomac area and USGS 0.3-meter resolution orthophotos for viewing when zoomed down on the areas of interest. Using orthophotos is much easier than trying to recreate the landscape with point, line, and polygon features, and it provided a more realistic depiction.

The next steps involved processing the hydrodynamic inundation model output data and creating raster overlays for each time increment. The water elevation value for each grid cell center point is selected from the main dataset and then run through a spline interpolation to generate a raster image of the data with the water elevation as the z-value. Using the LIDAR data, the flood overlays were then clipped in such a way as to only show those raster cells which were higher in elevation than the land surface. The result was a much finer visualization of the flood boundary than using the model grid outputs alone.

To speed the processing time for the purpose of this prototype demonstration, we re-sampled the LIDAR data from its original 1x1 meter to a 10x10 meter resolution. However, even with this resolution, processing each time increment was lengthy, and significant computing capacity will be required to provide operational time-scale products of sufficient spatial resolution for needed street-specific planning by emergency managers. The animation of the time step layers provides important insight through the display of changing water depths (noted by different colors or shades of blue in this prototype) and, when combined with the water velocity vectors, the emergency managers will have both an illustrative and quantitative forecast product to assist planning and operations.

Future visualization efforts may include the integration of three-dimensional depictions of physical structures and three-dimensional animations of inundation conditions to provide users with additional insight into the impact of flooding on localized infrastructure. In addition to emergency managers, these displays will also be valuable for other users, such as building designers and the insurance industry. These high-resolution visualizations will require highly accurate DEMs that include the vertical dimensions of structures in addition to land elevation data. Inundation analyses and forecasts must be validated and must have comparable vertical accuracy for these products to have credible value.

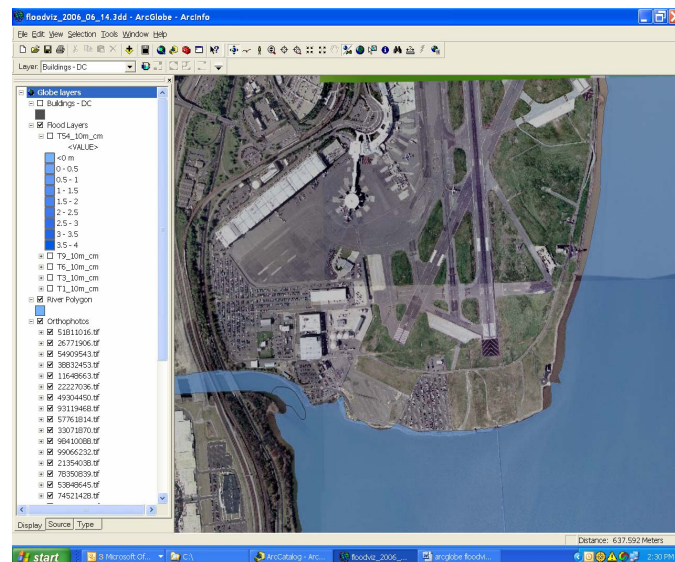


Figure 6. ICOFWS depiction of Washington Reagan National Airport before arrival of Hurricane Isabel.

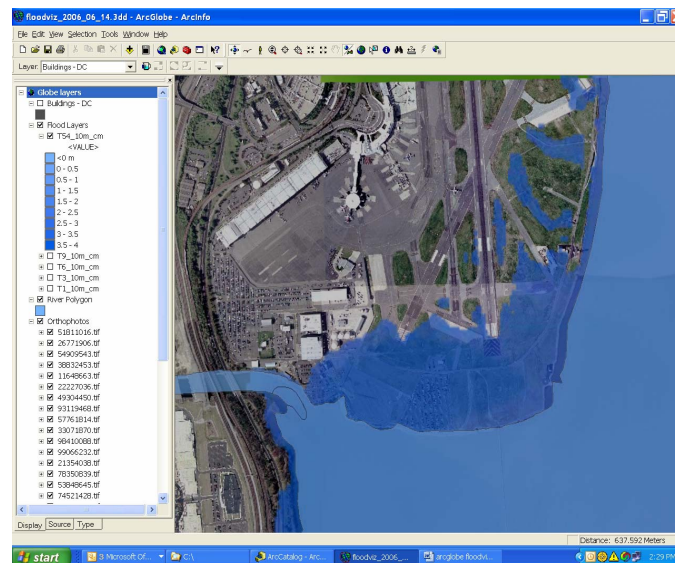


Figure 7. ICOFWS depiction of Washington Reagan National Airport at peak flooding during Hurricane Isabel.

III. WORKING WITH EMERGENCY MANAGERS AND PLANNERS RESPONSIBLE FOR FLOODING EVENTS

NWS predicts the height of the storm surge to provide local emergency managers and planners with accurate and timely information on possible flooding. Planners use this information to identify areas that flood under various conditions, develop land use plans and regulations based on the predicted flooding potential, and prepare emergency plans for dealing with flooding events. During storms, emergency managers and responders need timely and accurate predictions of flooded areas and depths to determine which areas should be evacuated and when to issue evacuation notices; to identify the threat to vulnerable facilities, such as hospitals, nursing homes, public utilities, and critical infrastructure; and to adjust response actions to the flooding as it occurs, such as routing emergency vehicles to avoid flooded roads and areas. NOAA has surveyed emergency and other planners and responders involved with storm-surge flooding to identify their needs [10] and identified shortcomings in the current prediction capability and products available to emergency professionals and the public.

Using this NOAA survey as a starting point, we began working with regional emergency managers to identify needs specific to the Washington Metropolitan Area and the tidal Potomac region. We are reviewing support issues with individual jurisdiction emergency managers and planners, and through the Metropolitan Washington Council of Governments and other regional agencies, so that the direction of the project will meet their needs. We are analyzing with them the results of initial inundation modeling and possible output types using visualization techniques. This coordination will identify how ICOFWS can be most useful to managers for planning and response and for effectively communicating predicted storm flooding to the public.

IV. PROTOTYPE DEMONSTRATION AND FUTURE ACTIONS

The culmination of this initial work is demonstrating the capabilities to those who could integrate the results into operational forecast services and who would benefit from those improved services. In addition to this prototype inundation forecast model with its associated databases, we are providing a state-of-the-art demonstration of visualization for both product users and the public. Interaction will continue with the many levels and programs of IOOS, primarily with MACOORA to demonstrate the value of this collaborative interaction of organizations operating in and providing support within the Chesapeake Bay region and to build further on this initial work. This prototype approach will also need to be evaluated for use with other IOOS regional associations throughout the United States. We will also continue close coordination with other developing projects in government, academia, and industry, such as the NOAA Gulf of Mexico Storm Surge Partnership Project and others through NOAA's Coastal Services Center.

The other key work that will enhance the viability, economy, and utility of this prototype approach is to complete the elements of systems engineering and program management that continually prove essential to successful programs. We

have begun to construct requirements from the needs and drivers expressed by users and providers. Developing the concept of operations, systems architecture, engineering plans, and program management plans will further the full scope of this project from identification of sensor needs to assimilation of improved modeling and support functions into operational agencies, local governments, industry, and for academic partners who still have much research to pursue for the full value of this capability.

As with any initial work, there is still much to be done. The primary intent was to assemble elements that were available and affordable with the scheduled time and resources. We acknowledge that these initial model couplings may not be optimum, and further collaboration is needed with similar programs. The process will require verifying and validating models (to the degree possible with previous storms and through future field work), establishing a sufficient observational network to support accurate forecasting, comparing to other models and visualization capabilities, defining roles and responsibilities of federal, state, and local governments, and integrating with programs in other geographic regions to achieve the best possible national flood-warning system. This project developed an initial capability through rapid prototype development and established the foundation for the next steps towards the transition to operations.

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